Materials Science

What Is Materials Science?

Materials science is an extremely broad field that encompasses the study of all materials. Materials scientists seek to understand the formation, structure, and properties of materials on various scales, ranging from the atomic to the microscopic to the macroscopic (large enough to be visible). Establishing quantitative and predictive relationships between the way a material is produced (processing), its structure (how the atoms are arranged), and its properties is fundamental to the study of materials.

Materials exist in two forms: solids and fluids. A fluid is any material that flows in response to an applied force. Gases such as air and helium are fluids, as are liquids like water, oil, and molten aluminum.

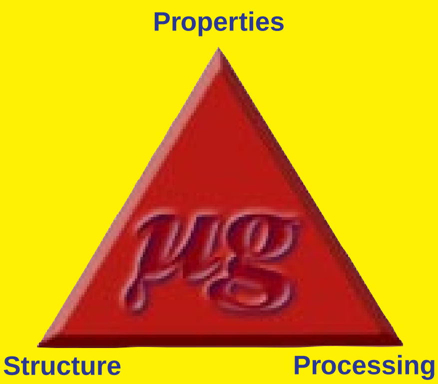
Solids can also be subdivided into two categories — crystalline and noncrystalline (amorphous) — based on the internal arrangement of their atoms or molecules. Metals (such as copper, steel, and lead), ceramics (such as aluminum oxide and magnesium oxide), and semiconductors (such as silicon and gallium arsenide) are all normally crystalline solids because their atoms form an ordered internal structure. Most polymers (such as plastics) and glasses are amorphous solids, which means that they do not have a long-range, specifically ordered atomic or molecular arrangement.

On the cover: Longitudinal section of a gallium-doped germanium crystal grown in a sounding rocket experiment. In the bottom portion of the crystal, which solidified under acceleration during launch, variations in gallium concentration in the crystal (caused by turbulent convection in the melt) are seen as random striations. The top portion of the crystal was grown under microgravity conditions, in which buoyancy-driven convection is absent; hence, the lack of striations. The evenly spaced lines in the upper part of the crystal are intentionally introduced time markers that indicate that the crystal was growing at a constant rate.

Marshall Space Flight Center in Huntsville, Alabama, is NASA's Microgravity Center of Excellence for materials science.

Why Conduct Materials Science Research in Microgravity?

One principal objective of microgravity materials science research is to gain a better understanding of how gravity-driven phenomena affect the solidification and crystal growth of materials. Primarily, materials processing is affected by buoyancy-induced convection (fluid flow resulting from temperature-driven density differences within the fluid), sedimentation (settling of different materials into distinct layers), and hydrostatic pressure (due to the weight of material above the point of measurement). These gravity-induced effects can create irregularities, or defects, in the internal structure of materials, which in turn alter the materials' properties. In microgravity, these gravity-driven phenomena are significantly suppressed, allowing researchers to study underlying events that would otherwise be obscured and therefore difficult or impossible to study quantitatively on Earth. For example, in microgravity, where buoyancy-driven convection is greatly reduced, scientists can carefully and quantitatively study segregation, a phenomenon that influences the distribution of a solid's components as it forms from a liquid or gas. (See back page for more information about microgravity, or µg.)



Many materials scientists use a triangle such as this to describe the relationship between structure, processing, and properties. Microgravity (μg) can play an important role in establishing these relationships in a quantitative and predictive manner.

Microgravity also supports an alternative approach to studying materials called containerless processing. Containerless processing has an advantage over normal processing in that containers, on the ground and in space, can contaminate the materials being processed inside them. In addition, there are some cases in which there are no containers that will withstand the very high temperatures and/or corrosive environment needed to work with certain materials. Containerless processing, in which acoustic, electromagnetic, or electrostatic forces are used to position (levitate) and manipulate a sample, thereby eliminating the need for a container, is an attractive solution to these problems.

Although containerless processing can be accomplished on Earth, the forces required to levitate samples are so strong that they can interfere with and influence the behavior of the material (for example, turbulent fluid flows can be induced in the sample). Microgravity requires much smaller forces to control the position of containerless samples, so the materials being studied are not disturbed as much as they would be if they were levitated on the ground.

Researchers in materials science are particularly interested in increasing their fundamental knowledge of the physics and chemistry of phase changes (when a material changes from liquid to solid, gas to solid, etc.). This knowledge could be applied to designing better process-control strategies in laboratories and production facilities on Earth. In addition, microgravity experimentation may eventually enable the production of limited quantities of high-quality materials and of materials that exhibit unique properties for use as benchmarks.

Microgravity researchers are interested in studying various methods of crystallization, including solidification (like freezing water to make ice cubes), crystallization from solution (the way rock candy is made from a solution of sugar and water), and crystal growth from the vapor (like frost forming in a freezer). These processes all involve fluids, which are the materials that are most influenced by gravitational effects. Examining these methods of transforming liquids or gases into solids in microgravity gives researchers insight into other influential phenomena at work in the crystallization process.

Materials Science Research Areas

Electronic Materials

Electronic materials play an important role in the operation of computers, medical instruments, power systems, and communications systems. Semiconductors are well-known examples of electronic materials and are a primary target of microgravity materials science research. Applications include creating crystals for use in lasers; computer chips; solar cells; and X-ray, gamma-ray, and infrared detectors. Each of these devices depends on the ability to manipulate the crystalline and chemical structure of the material, which can be strongly influenced by gravity as crystals are formed.

The properties of electronic materials are directly related to the chemical and crystalline perfection of the material. However, perfect crystals are not normally the ultimate goal. The presence of just a few intentional impurities in some electronic materials can drastically affect their ability to conduct electricity. By carefully controlling crystalline defects and the introduction of desirable impurities into the crystals, scientists and engineers can design better electronic devices with a wider range of applications.

Glasses and Ceramics

A glass is any material that is formed without a long-range ordered arrangement of atoms. Materials that naturally form glasses have liquid and chemical bonding properties that prevent atoms from aligning into crystalline structures as the liquid cools. One important aspect of glass formation is the limited mobility of the atoms in the liquid form of the material. This sluggishness of atomic movement is one of the things that prevents the formation of a crystalline solid. Some materials that usually take crystalline forms, like metals, can also be forced to form glasses by rapidly cooling the molten materials to temperatures far below their normal solidification point. When the materials finally solidify, they freeze so quickly that the normally mobile atoms or molecules do not have time to arrange themselves systematically.

Ceramics are inorganic nonmetallic materials that can be extraordinarily strong at very high temperatures, performing far better than metallic systems under certain circumstances. They will have many more applications when important fundamental problems can be solved. If a ceramic turbine blade, for example, could operate at high temperatures while maintaining its strength, it would provide overall thermodynamic and fuel efficiencies that would revolutionize transportation. The problem with ceramics is that when they fail, they fail catastrophically, breaking in an irreparable manner.

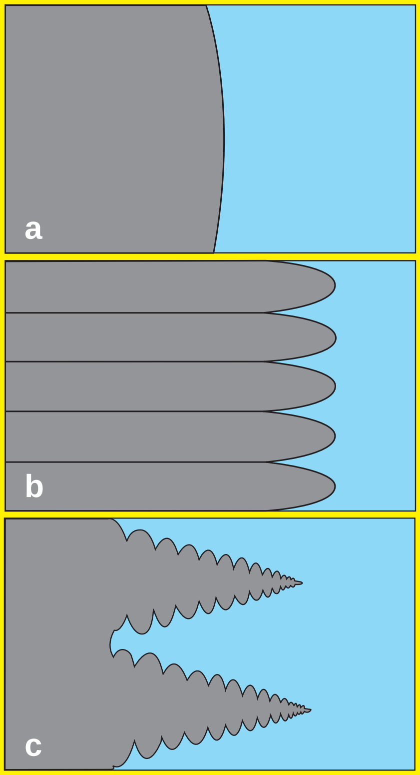
Glasses and ceramics are generally unable to absorb the impacts that metals can; instead, they crack under great force or stress (whereas metals generally bend before they break). An important part of ceramics and glass research in microgravity involves controlling the minute flaws that govern how these materials fail. From information obtained through microgravity research, scientists hope to be able to control the processing of glasses and ceramics well enough that they can, during processing, prevent the formation of imperfections that lead to catastrophic failure.

Applications for knowledge obtained through research in these areas include improving glass fibers used in telecommunications and creating high-strength, abrasion-resistant crystalline ceramics used for gas turbines, fuel-efficient internal combustion engines, and bioceramic artificial bones, joints, and teeth.

Metals and Alloys

Metals and alloys (combinations of two or more metals) constitute an important category of engineered materials, which include electrical conductors, many types of composites, and structural and magnetic materials. Research in this area is primarily concerned with advancing the understanding of metals and alloys processing so that structure and, ultimately, properties can be controlled as the materials are originally formed. By removing the influence of gravity, scientists can more closely observe important processes in structure formation during solidification. The properties of metals and alloys are linked to their crystalline and chemical structure; for example, the mechanical strength and corrosion resistance of an alloy are determined by its internal arrangement of atoms, or its microstructure, which develops as the metal or alloy solidifies from its molten state.

One aspect of the solidification of metals and alloys that influences their microstructure is the shape of the boundary, or interface, that exists between a liquid and a solid in a solidifying material. As the rate of solidification increases under the same thermal conditions, the shape of the solidifying interface goes through a series of transitions.



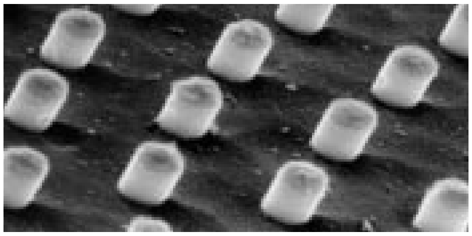
*Representations of the different shapes of the liquid/solid interface in a solidifying material: planar (**a**), cellular (**b**), and dendritic (**c**).*

At low growth rates, the interface is planar (flat or smoothly curved on a macroscopic scale). As the growth rate increases, the interface develops a corrugated texture until three-dimensional cells form in the solid. A further increase in growth rate causes the formation of dendrites (tree-shaped structures) in the solid. The development of these different interface shapes and the transition from one shape to another is controlled by the morphological stability of the interface, which is influenced by many factors, including buoyancy-driven convection. Data obtained about the conditions under which certain types of solidification boundaries appear can help to explain the evolution of the final microstructure of a material.

Another area of interest in metals and alloys research in microgravity is multiphase solidification. Certain materials known as eutectics and monotectics transform from a single-phase liquid to substances of more than one phase when they are solidified. When these materials are processed on Earth, the resulting solid structures show the influence of gravity-induced effects (buoyancy-driven convection and/or sedimentation). But when these materials are processed in microgravity, theory predicts that the end product should consist of an evenly dispersed, multiphase structure. Eutectic and monotectic alloys with this type of internal structure may be useful for specialized applications such as superconductors, high-performance magnets, bearing materials for engines, catalysts, and electrical contacts.

A eutectic solidifies from one liquid of uniform composition to form two distinct solid phases. An example of such a material is the alloy manganese-bismuth (Mn-Bi). Solidifying liquid Mn-Bi results in two different solids, each of which has a chemical composition that differs from the liquid. In eutectic solidification in microgravity, one solid (the minor phase) is distributed as rods, particles, or layers throughout the other solid (a continuous matrix, or the major phase).

Monotectics are similar to eutectics, except that a monotectic liquid solidifies to form a solid and a liquid (both of which are different in composition from the original liquid). Aluminum-indium (Al-In) is a monotectic that starts out as indium dissolved completely in aluminum, but when the alloy is solidified under the appropriate conditions, it forms a solid aluminum matrix with long thin “rods” of liquid indium inside it. As the system cools, the rods of liquid indium freeze into solid rods. These indium rods are dispersed within the structure of the solidified material.



An etched sample of the aluminum-indium alloy (magnified). When the monotectic mixture is cooled, aluminum transitions to a solid first, trapping the indium in cylindrical “rods” within the solid.

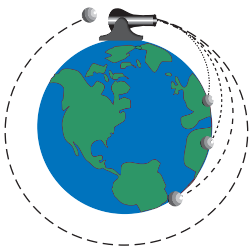
Polymers

Polymers are organic macromolecules (very large molecules) made up of numerous small repeating molecular units called monomers. They appear naturally in wool, silk, and rubber and are manufactured in the form of acrylic, nylon, polyester, and plastic. Important optoelectronic and photonic applications are emerging for polymers, and many of the properties needed for these applications are affected by the polymers’ crystallinity. This crystallinity, which is the extent to which chains of molecules line up with each other when the polymer is formed, may be more easily manipulated when removed from the influence of gravity.

Polymers are typically composed of long chains of monomers. These chains appear to have a spine of particular elements such as carbon or nitrogen. The bonding between individual polymer molecules affects the material’s physical properties such as surface tension, miscibility, and solubility. Manipulation of these bonds under microgravity conditions may lead to the development of processes to produce polymers with more uniform and controlled specific properties.

Growing polymer crystals can be more difficult than growing inorganic crystals (such as semiconductors) because the individual polymer molecules weigh more and are more structurally complex, which hinders their ability to attach to a growing crystal in the correct position. Yet in microgravity, the process of polymer crystal growth can be studied in a fundamental and systematic way, with special attention to the effects of such variables as temperature, compositional gradients, and the size of individual polymer units on crystal growth. In addition, just as microgravity enables the growth of larger protein crystals, it may allow researchers to grow single large polymer crystals for use in studying the properties of polymers and determining the effects of crystal defects on those properties.

Gravity and Microgravity



In his "thought experiment," Isaac Newton hypothesized that by placing a cannon at the top of a very tall mountain and firing a cannonball at a high enough velocity, the cannonball could be made to orbit the Earth.

Gravity is such an accepted part of our lives that we rarely think about it, even though it affects everything we do. Any time we drop or throw something and watch it fall to the ground, we see gravity in action. Although gravity is a universal force, there are times when it is not desirable to conduct scientific research under its full influence. In these cases, scientists perform their experiments in microgravity — a condition in which the effects of gravity are greatly reduced, sometimes described as "weightlessness." This description brings to mind images of astronauts and objects floating around inside an orbiting spacecraft, seemingly free of Earth's gravitational field, but these images are misleading. The pull of Earth's gravity actually extends far into space. To reach a point where Earth's gravity is reduced to one-millionth of that on Earth's surface, one would have to be 6.37 million kilometers away from Earth (almost 17 times farther away than the Moon). Since spacecraft usually orbit only 200–450 kilometers above Earth's surface, there must be another explanation for the microgravity environment found aboard these vehicles.

Any object in freefall experiences microgravity conditions, which occur when the object falls toward the Earth with an acceleration equal to that due to gravity alone (approximately 9.8 meters per second squared [m/s^2], or 1 g at Earth's surface). Brief periods of microgravity can be achieved on Earth by dropping objects from tall structures. Longer periods are created through the use of airplanes, rockets, and spacecraft. The microgravity environment associated with the space shuttle is a result of the spacecraft being in orbit, which is a state of continuous freefall around the Earth. A circular orbit results when the centripetal acceleration of uniform circular motion ($\mathbf{v}^2/\mathbf{r}$; $\mathbf{v}$ = velocity of the object, $\mathbf{r}$ = distance from the center of the object to the center of the Earth) is the same as that due to gravity alone.

Microgravity Research Facilities

A microgravity environment provides a unique laboratory in which scientists can investigate the three fundamental states of matter: solid, liquid, and gas. Microgravity conditions allow scientists to observe and explore phenomena and processes that are normally masked by the effects of Earth's gravity.

NASA's Microgravity Research Division (MRD) supports both ground-based and flight experiments requiring microgravity conditions of varying duration and quality. These experiments are conducted in the following facilities:

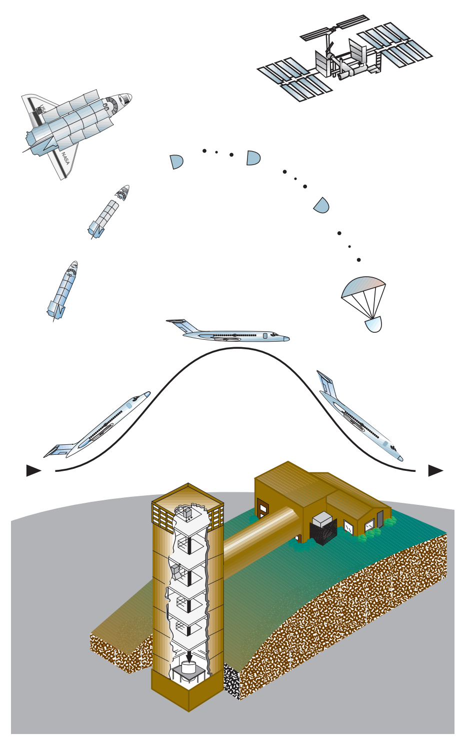
A **drop tower** is a long vertical shaft used for dropping experiment packages, enabling them to achieve microgravity through freefall. Various methods are used to minimize or compensate for air drag on the experiment packages as they fall. Lewis Research Center in Cleveland, Ohio, has two drop facilities (one 24 meters tall and one 132 meters deep) that can accommodate experiments which need only a limited amount of time (2.2 or 5.2 seconds) in microgravity or which are test runs of experiments that will later be performed for longer periods in an aircraft, rocket, or spacecraft.

Reduced-gravity aircraft are flown in parabolic arcs to achieve longer periods of microgravity. The airplane climbs rapidly until its nose is at an approximate 45-degree angle to the horizon. Then the engines are briefly cut back, the airplane slows, and the nose is pitched down to complete the parabola. As the plane traces the parabola, microgravity conditions are created for 20–25 seconds. As many as 40 parabolic trajectories may be performed on a typical flight.

Sounding rockets produce higher-quality microgravity conditions for longer periods of time than airplanes. An experiment is placed in a rocket and launched along a parabolic trajectory. Microgravity conditions are achieved during the several minutes when the experiment is in freefall prior to re-entering Earth's atmosphere.

A **space shuttle** is a reusable launch vehicle that can maintain a consistent orbit and provide up to 17 days of high-quality microgravity conditions. The shuttle, which can accommodate a wide range of experiment apparatus, provides a laboratory environment in which scientists can conduct long-term investigations.

A **space station** is a permanent facility that maintains a low Earth orbit for up to several decades. The facility enables scientists to conduct their experiments in microgravity over a period of several months without having to return the entire laboratory to Earth each time an experiment is completed.



Microgravity Research Division